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DIMENSIONS NBS

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OF COMMERCE

Electrical Measurement System

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CONTENTS

267 Basis of the U.S. National Electrical Measurement System
272 Fire Safety for New Subway in Nation's Capital
274 The Rise of the Calculable Capacitor
278 Using Computer Simulation to Solve Problems
282 Highlights
283 Computer-Aided Manufacturing Can Increase Productivity
284 Energy-Environment Workshops Planned
284 NBS Guides Consumers in Use of Color
288 Index

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DIMENSIONS NBS
I:V/R
Electrical Measurement System

Cover: Ohm's Law, first stated in 1827, expresses the relationship between current, I, voltage, V, and resistance, R, in an electric circuit. The relationship between Ohm's Law and the National Electrical Measurement System is explained in the article beginning on the opposite page.

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The National Bureau of Standards serves as a focal point in the Federal Government for assuring maximum application of the physical and engineering sciences to the advancement of technology in industry and commerce. For this purpose, the Bureau is organized as follows:
The Institute for Basic Standards
The Institute for Materials Research
The Institute for Applied Technology
The Institute for Computer Sciences and Technology
Center for Radiation Research
Center for Building Technology
Center for Consumer Product Technology
Center for Fire Research

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The famous physicist Lord Kelvin claimed, ". . . when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind."

One of the main responsibilities of the National Bureau of Standards is to provide for the Nation the kind of understanding Lord Kelvin was talking about—knowledge through measurement—for the basic quantities, including electricity.

When the Bureau was founded in 1901, the vast potential of "portable" electric power was just beginning to be realized. A critical need had yet to be met—knowledge of electricity through adequate measurement techniques and measurement standards. In the last 75 years NBS has provided, and continues to refine, a national measurement system for electricity that meets the increasingly sophisticated needs in science and commerce.

The following article is a capsule description of this system today.

THE electrical units now universally employed in the United States are those of the International System of Units ("SI units" for short). They are also the same as the "rationalized MKSA" units familiar to electrical engineers.

If all existing electrical standards were destroyed, it would be possible to reconstruct them accurately on the basis of their definition—provided we also had access to accurate standards of length (meter), mass (kilogram) and time (second). In practice, the "absolute determination" of electrical units, as the construction and evaluation of primary electrical standards is called, is rarely undertaken except by national standards laboratories like the National Bureau of Standards.

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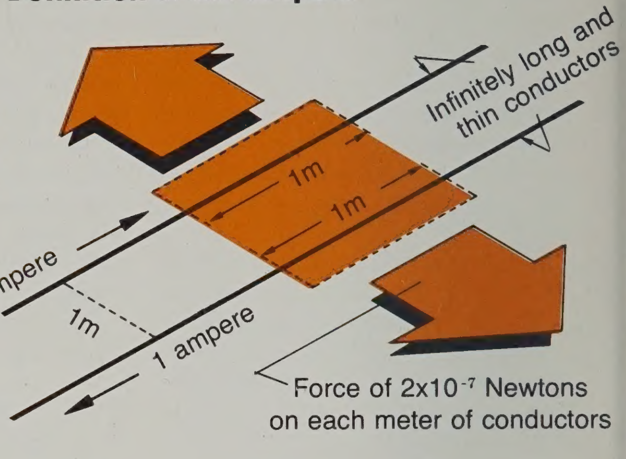
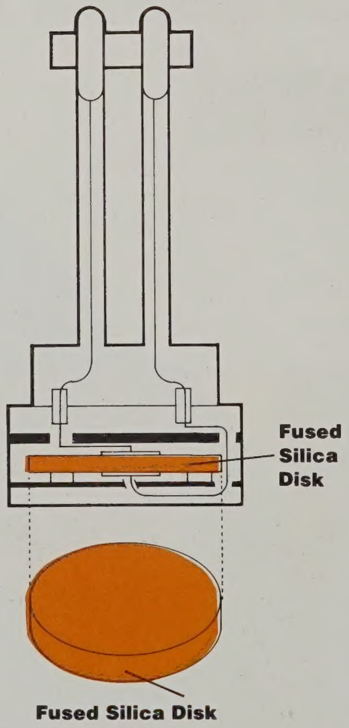
Basis of the U.S. National Electrical Measurement System

Definition of the Ampere


Infinitely long and thin conductors
1m
1m
1 ampere
1m
1 ampere
Force of $2x10^{-7}$ Newtons on each meter of conductors

The ampere is defined in terms of the force per meter between two infinitely long wires when a current of 1 ampere is flowing through them.

NBS 10-picofarad reference capacitor is of the parallel-plate type. The 'plates' are the upper and lower silvered surfaces of a circular disk of fused silica (quartz). The fused silica disk (approx. diam. 7 cm, thickness 1 cm) is also shown separately at bottom.



The Measurement Strategy

Three units are considered the starting point of the electrical measurement system as it exists today: the unit of current (the *ampere*), the unit of electromotive force or potential difference (the *volt*), and the unit of resistance (the *ohm*). Once the standards for any two of these units are established they can be used to calibrate standards of the third one.

The first step in the NBS measurement strategy is to build a capacitor whose capacitance can be calculated very accurately from its dimensions. Then, by means of an alternating-current bridge, a resistance standard can be calibrated by comparing its resistance with the impedance of the calculable capacitor.

Every 10 years or so an absolute determination is made of the ampere: A current is created in a special apparatus which permits the current to be evaluated in terms of the definition of the ampere. Such a current can be accurately maintained for only a few minutes. This is time enough to use this current, together with the ohm standard, to calibrate voltage cells (batteries specially designed to serve as standards). A group of these cells constitute the working standard of voltage which, unlike the ampere standard, can be available at all times.

In principle, a different measurement strategy might have been adopted. Some, for example, would consider it simpler to start by defining the unit of electric charge, the *coulomb,* instead of the ampere (which would then be defined as a current flow of 1 coulomb per second). Or, instead of taking a calculable capacitor as a primary standard, a calculable inductor—a coil whose inductance we can calculate from its dimensions—might have been chosen. This was in fact the procedure followed until the recent improvements in the accuracy of the calculable capacitor gave it a decisive advantage. (See "The Rise of the Calculable Capacitor," page 274.) Deciding which units to start with, and what kinds of standards to embody them in, represents a complex judgment on how to optimize the quality of electrical measurements. Two obviously important technical criteria are that the standards should represent the units as accurately as possible and that they be as stable (constant) as possible.

Consequently, changes in both the starting units and types of standards can be expected from time to time as a result of advances in experimental technique and theoretical understanding. Much hard thought is in fact presently being given, at NBS and elsewhere, to potential improvements or alternatives to the existing procedures and standards.

Some Definitions

(Note: Statements in quotation marks are definitions adopted by the 19th General Conference of Weights and Measures in 1948.)

Current: Physically, an electric current is a flow or drift of charged particles—electrons, in the case of a metallic conductor of electricity. A moving charge, however, is accompanied by a magnetic field, which gives rise to forces between conductors in which currents are flowing. This fact is utilized in the definition:

"The *ampere* is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible cross section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length."

Electromotive force (emf)/potential difference (p.d.): A device that converts other forms of energy into electrical energy (for example, a storage battery or steam-driven electric power generator) is said to be a source of emf. Such a source has the ability to drive an electric current around a circuit of which it is part. The emf is measured in *volts,* the number of volts being equal to the number of joules of energy imparted by the source to each coulomb passing through it.

The current maintained by an emf is produced by electric fields that drive the mobile current carriers (for example, electrons). The p.d. between two points in such a circuit, also expressed in volts, is the work, in joules, done by these fields on each coulomb that passes from one point to the other. In a pure resistor, all this energy is converted to heat, which leads to the definition:

"The *volt* is the difference of electric potential between two points of a conducting wire carrying a constant current of 1 ampere, when the power dissipated between these points is equal to 1 watt." (1 watt = 1 joule per second)

Resistance: A resistor, as mentioned, is a conductor in which all of the electrical energy is converted to heat. Resistors obey Ohm's law: the current in a resistor is proportional to the p.d. across its ends. The resistance, in *ohms,* is the number of volts of p.d. needed to produce a current of 1 ampere through the resistor, or:

"The *ohm* is the electric resistance between points of a conductor when a constant potential difference of 1 volt, applied to these points, produces in the conductor a current of 1 ampere, the conductor not being the seat of any electromotive force."

Capacitance: Any pair of electrical conductors separated by a nonconductor is a capacitor. If equal and opposite charges are given to the two conductors, the p.d. between them is found to be proportional to the charge. The number of coulombs required to bring the p.d. up to 1 volt is the capacitance, in *farads,* of the capacitor. Since capacitance is affected by changes in the position of nearby conductors, precision capacitors are enclosed in a metal envelope or shield (normally connected to a ground) that practically eliminates such changes.

A capacitor can also be characterized by its dynamic behavior. If we apply to a capacitor an alternating emf, i.e., one that pushes the electrons alternately onto one of the conductors of the capacitor, then onto the other, but changing smoothly according to a sine-wave law, then the current also changes according to a

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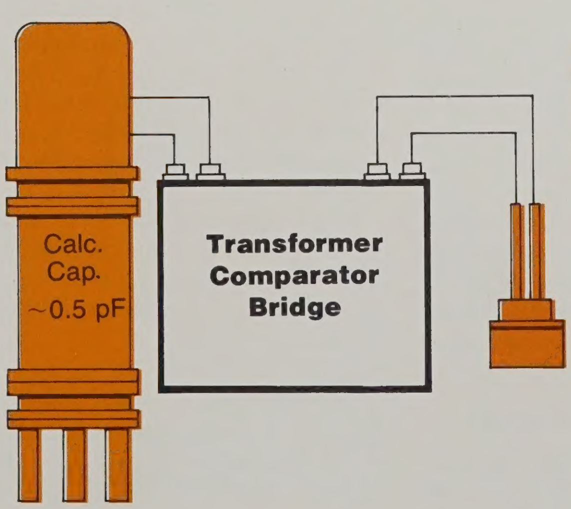
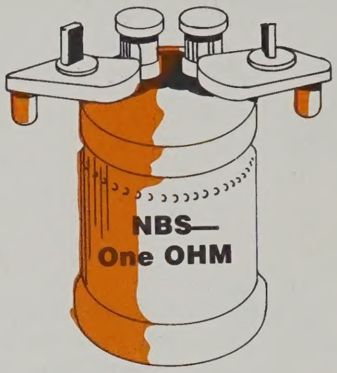
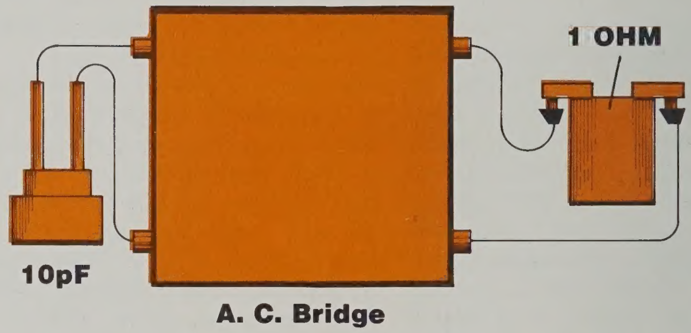


Measuring NBS reference capacitor against the calculable capacitor. Bridge circuits play a role in comparing electrical quantities like that of balances in comparing masses.



NBS 1-ohm reference resistor. Resistance is provided by a length of manganin wire inside a hermetically sealed container. Manganin is an alloy (85 percent copper, 12 percent manganese, 3 percent nickel) whose resistance is very little affected by changes in ambient temperature.

Resistance of a reference resistor is measured with an alternating-current bridge, which compares it with the impedance, at a known frequency, of a capacitor that has been calibrated against the calculable capacitor.



Electrical *continued*

sine-wave law. If the same alternating voltage is applied in turn to several capacitors, the amplitudes (peak values) of the alternating currents produced will be proportional to the capacitances in farads. For a given capacitor, the current amplitude is proportional to both the voltage amplitude and to the frequency. At a given frequency, the *impedance* of the capacitor, in *ohms*, is equal to the voltage amplitude needed to produce a current amplitude of 1 ampere. In a pure capacitance, the current wave leads the voltage wave by one-quarter of a cycle.

Inductance: Inductance has been described as the electrical counterpart of inertia—i.e., as a tendency to resist changes in electric current. The resistance to change takes the form of an induced voltage that pushes electric charges in the direction that minimizes the current change.

Any conductor has inductance, but it is more pronounced when the conductor is in the shape of a coil, and the more turns the higher the inductance. The SI unit of inductance is the *henry:* a coil has an inductance of 1 henry if a p.d. of 1 volt is induced across its terminals when the current through it changes at the rate of 1 ampere per second. The impedance of an inductor is defined in the same way as for a capacitor and it is also expressed in ohms. But in contrast to a capacitive impedance, the impedance of an inductor *increases* as the frequency increases and the current wave *lags* the voltage wave by a quarter cycle.

Electrical Standards at NBS

In accordance with the "measurement strategy" outlined above, NBS has constructed standards that embody, as well as the present state-of-the-art permits, the SI units of capacitance, resistance, current and emf/p.d. The SI definitions, some of which are quoted above, relate the electrical units to each other and to the meter, kilogram, and second. The definition of the ampere, for example, relates it to the *newton*—the force that, when applied to a mass of 1 kilogram, gives it an acceleration of 1 meter per second per second.

In the following, all uncertainties are expressed in parts per million (ppm) and are based on estimates at the 95 percent confidence level (2 standard deviations).

Capacitance: the farad

The NBS standard of the farad is a specially designed variable capacitor of the Thompson-Lampard type that has been developed over the past 20 years. One can calculate the amount by which its capacitance changes when a grounded metal rod passing through its center is moved through a distance measured by an interferometer with light from a stabilized laser. The calculated change in capacitance, expressed in farads, depends on the value of the speed of light.

The U.S. legal farad, F_{NBS}, is the average capacitance of a group of 5 reference capacitors, each about 10 picofarads, that have been calibrated against the primary standard. F_{NBS} is believed to be equal to the farad as defined, i.e., to the SI farad, to within 0.02 ppm.

Resistance: the ohm

The U.S. legal ohm is based on the average resistance of 5 reference resistors of close to 1 ohm each, maintained (like all the other national

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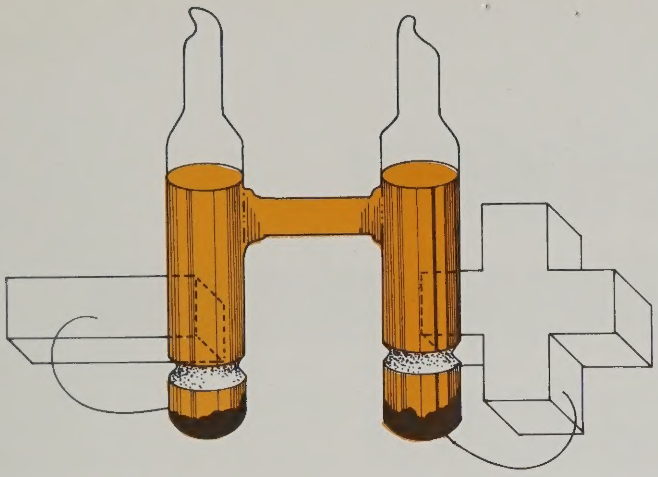
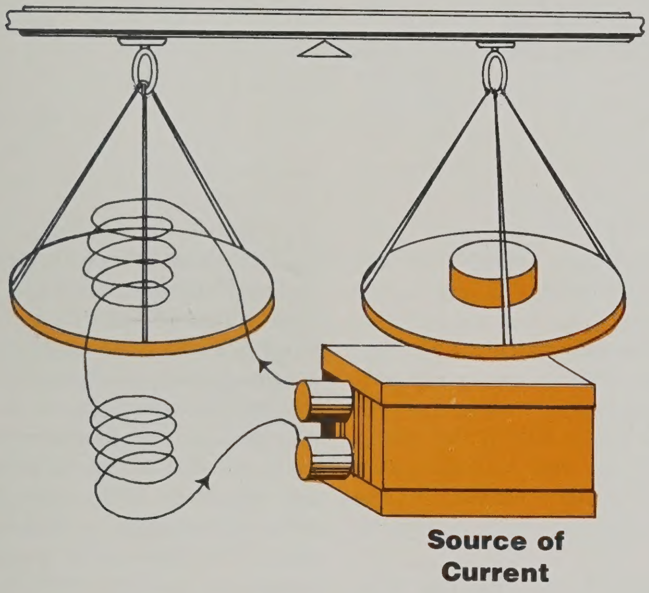
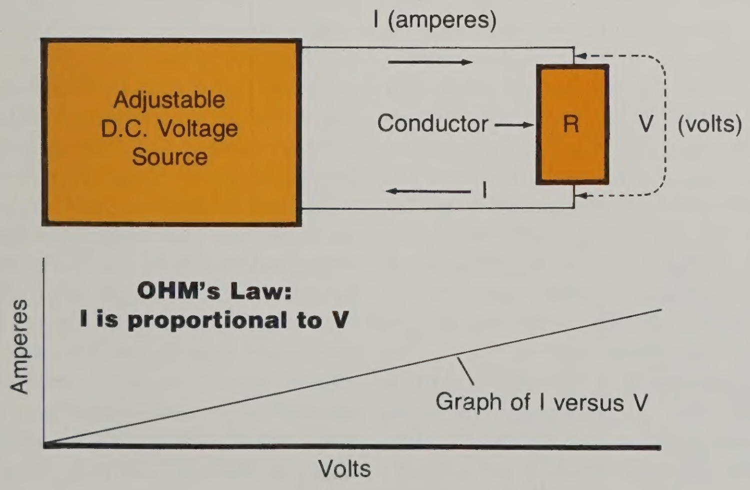


Standard cell of the saturated cadmium sulfate type. A group of these special batteries forms the working standard of the U.S. legal volt.



Principle of the Current Balance. The size of the current, in amperes, is found by measuring the magnetic force between two coils (whose dimensions must also be measured) through which the current flows. The force is determined by balancing it against the weight of a known mass.



Ohm's law. The resistance R (ohms) of a conductor = V/I, the voltage across the conductor divided by the current I (amperes) through it. According to Ohm's law, for many conductors the value of the ratio, V/I, and therefore of R, is essentially constant over a usefully wide range of currents and voltages. In this range, I and V are proportional to one another: I = V/R or V = I•R.

Fire Safety for New Subway in Nation's Capital

FOR the past several years residents of the Nation's Capital have become used to traffic detours, wooden planks laid across heavily traveled thoroughfares, and earsplitting noise. Washington, D.C., is in the process of laying a subway system designed to speed commuters into the central city and serve as a showpiece for thousands of annual visitors.

The 98-mile, $4.6 billion system is in keeping with the Federal policy of encouraging the development of mass transit facilities rather than high-speed highways for private automobiles.

Washington's subway is being constructed by the Washington Metropolitan Area Transit Authority (WMATA), which is composed of representatives of the various local governments in Washington and its surrounding Virginia and Maryland suburbs. In May, 1974, an official representing Washington-area fire chiefs raised questions concerning the fire safety of the subway cars ordered for the system. He asked the National Bureau of Standards' Center for Fire Research for advice and opinion.

The NBS offer to serve as a consultant was accepted in June, 1974, by General Jackson Graham, General Manager of WMATA. The next month a task force was formed that included three NBS representatives, two local government officials and two WMATA representatives. During the next month this group visited the manufacturer of the cars and consulted with other transit systems. A few small-scale fire tests were conducted at NBS.

On August 19, 1974, this task force issued a report that recommended full-scale burn tests on a mock-up of an interior of one of the proposed cars. This, the group said, would provide a more accurate assessment of the fire risk. In making this recommendation, the task force said the fire load (materials in the car with potential for burning) was high enough so that a hazard could exist and that the smoke development potential of the seats and wall linings appeared to be high. Based on the experiences of other subway systems, ignitions in and under the Washington cars will occur, the group said.

Following this report, WMATA asked NBS to undertake full-scale testing in its new Fire Test Facility. While NBS and WMATA were working out the details of this program, a new, more-immediate problem arose. Several new WMATA buses had been burned. Public and news media interest was high and WMATA turned to NBS for assistance in evaluating the flammability of the interiors of these new buses. An inoperable bus was towed to NBS in March, 1975, full-scale tests were conducted, and a report was released at a press conference on May 15. NBS found the polyurethane foam padding in the bus seats a potential fire hazard and suggested that WMATA either remove the padding or cover it with a highly fire-resistant fabric. (DIMENSIONS, July, 1975, p. 154)

While this delayed the subway fire test project, it also offered NBS valuable experience in instrumenting and conducting tests of transit vehicles.

In June NBS technicians constructed a subway car mock-up in the Fire Research Facility. It was approximately one-fifth the length of a subway car, containing several row of seats, wall and ceiling panels, and floor carpeting. The mock-up was instrumented with thermocouples and an apparatus to measure gas concentrations. A total of 7 full-scale tests were run. In each test ignition was accomplished by lighting a paper bag placed on a seat or a wad of rolled newspaper placed under a seat. The results were recorded on videotape.

In addition to the full-scale tests, NBS scientists conducted a smoke test on an actual subway car. A smoke bomb was set off beneath the parked car, to test the floor's seal in the event of a fire beneath the carriage.

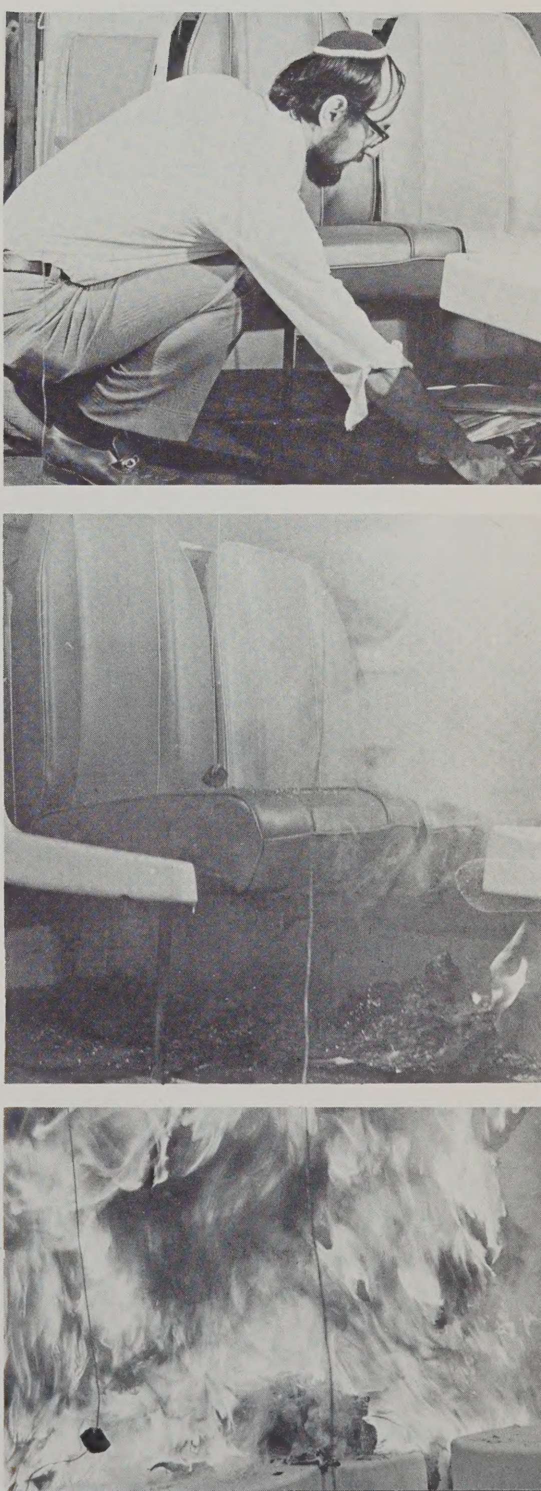
NBS also tested a total of 4 types of subway car seats—3 made of urethane foam and 10 of vinyl neoprene. All 3 urethane formulations were found to be readily ignited. Two of the seat types ignited when the trash bag was lighted; the third urethane seat, which had a higher flame retardant in the covering fabric, was ignited by the rolled newspaper.

The vinyl neoprene seat could be ignited by the rolled newspaper, but smoke and flame spread were found to be much less severe. NBS suggested that WMATA equip its cars with vinyl neoprene seats.

NBS fire researchers also found potential problems with the wall lining of the cars. Once the seats were ignited, the walls—made of polyvinylchloride acrylic—tended to become involved. To remedy this, NBS suggested replacing the panel with one of a more fire resistant material.

The smoke given off by the seats and walls was found to be hazardous because of its effects on reducing vision rather than due to the presence of any severely toxic agents. Smoke production, however, was rapid. After approximately 5 minutes there was only 10 percent vision left in the mock-up. With the vinyl neoprene seats, there was initial smoke buildup but this leveled off somewhat and did not reach the 10 percent level until about 9 minutes. NBS researchers attributed this difference to the fact that the fire was contained largely in the seat fabric and did not penetrate the cushion rapidly.

These results were released at a press conference on November 10. WMATA was already considering the possibility of changing the seat fabric from polyurethane foam to vinyl neoprene based on WMATA observations of early full-scale tests. The other NBS suggestions are also being studied by WMATA. ☐



Top. Emil Braun, NBS fire researcher, ignites pile of newspaper beneath vinyl neoprene seat in NBS mock-up of subway car. Center. Fifteen minutes into the test the underside of the neoprene seat has been damaged and is smoking. Flame, however, has not spread to adjacent seat or wall liner. Bottom. In a test of urethane seats, fire has engulfed one seat and spread to an adjacent seat and the wall lining after 8½ minutes. The wires hanging from the ceiling are thermo-couple lines used to measure the temperatures and gases.

The Rise of the Calculable Capacitor

It is No. 1 in accuracy among basic electrical standards
It determines the size of the ohm (as well as the farad)
It helps monitor the constancy of the ampere standard

The National Bureau of Standards has contributed significantly to one of the quieter revolutions of the last two decades—the upgrading of electrical measurement accuracy through development of the "calculable capacitor" as a standard. Quiet though the revolution may be, it has had a substantial positive influence on measurement quality where precision electrical measurements are important.

THE electric capacitor has come a long way in the science of measurement. Twenty years ago discussions of basic electric standards scarcely mentioned it. Today the SI or metric unit of capacitance, the *farad,* is the most accurately realizable of the electric units.

More impressive still, capacitance standards can now be used to measure the resistance in ohms of standard resistors. And the National Bureau of Standards is setting up a regular program for monitoring the U.S. legal ohm standard by comparing it periodically with the capacitance standard.

The capacitor's march to metrological glory began back in 1956 when A. M. Thompson and D. G. Lampard of the Australian National Measurement Laboratory (NML), then the National Standards Laboratory of Australia, discovered a new theorem in electrostatics. They uncovered a whole new class of designs, the "cross capacitors," whose capacitances can be calculated with unusual accuracy—in electrostatic units—from a single linear dimension of the capacitor.

However, to calculate a capacitance in SI units (farads)—which is indispensable for most practical applications of capacitors—it is necessary to know the speed of light. (The capacitance formula contains the factor, ϵ_0, the "permittivity of space," which in turn depends on c^2, the square of the speed of light). Hence any uncertainty in the speed of light will reappear (multiplied by 2, because the square of c is involved) in the uncertainty of the capacitance. This difficulty was soon eliminated by progress in measuring the speed of light at NBS Boulder Laboratories. The uncertainty is now below 0.01 part per million (ppm).(See DIMENSIONS/NBS, April 1974, pp. 90-91.)

An apparently more formidable obstacle in the path of the calculable capacitor was the extreme minuteness of a picofarad (pF). Its usefulness would therefore have been severely limited unless a way could be found to accurately compare such small capacitors with the very much larger ones that are most frequently used.

This difficulty was overcome when scientists at the Australian NML and at NBS succeeded in designing circuits (transformer comparator bridges) that can compare capacitors of only a fraction of a picofarad with capaci-

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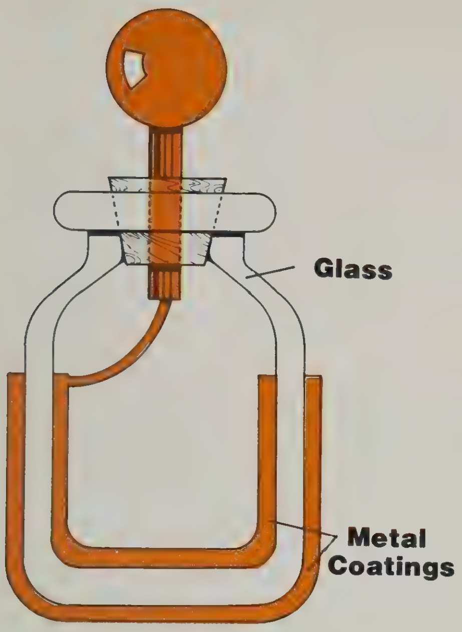
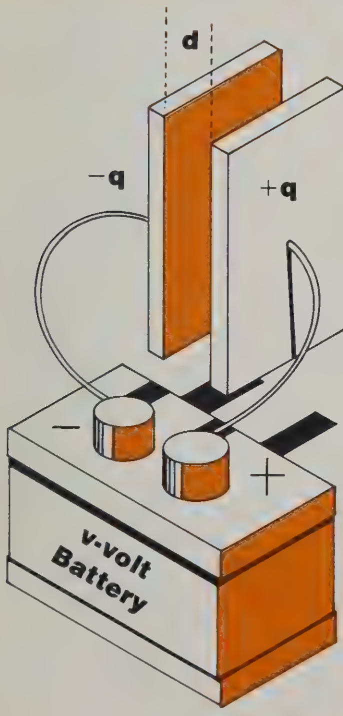


SOME BASICS ON CAPACITORS AND CAPACITANCE . . .

Any two conductors, with a nonconductor (the 'dielectric') between, can store electric charge.

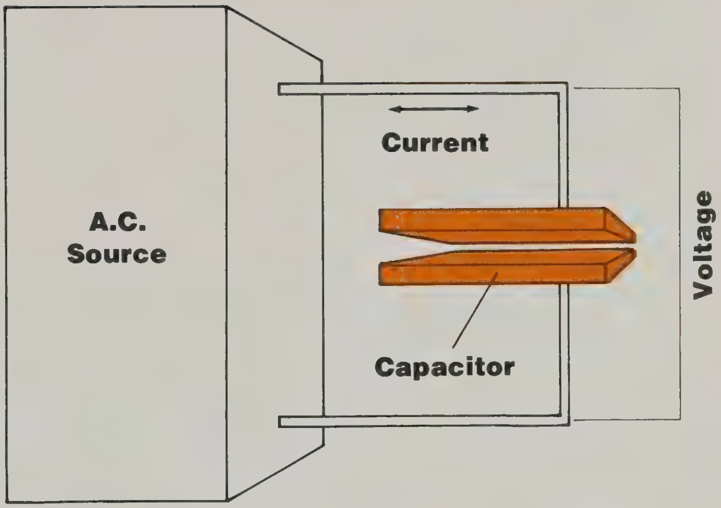
A capacitor is a pair of conductors specially designed to store appreciable amounts of charge (like a millionth of a coulomb)—its two conductors come close to each other over a fairly large area . . . as can be seen in the first capacitors, the 'Leyden jars' of the 18th century, one type of which is shown here in cross section. Glass is the dielectric; tin foil or silver leaf formed the conducting layers.



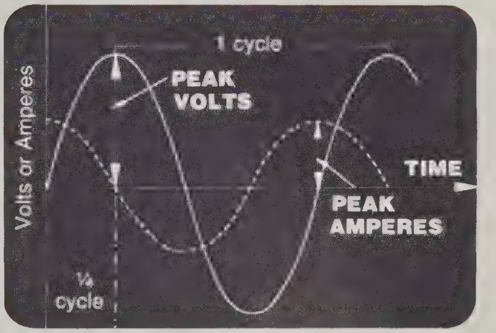
The capacitance C, in farads, is the number of coulombs stored on each conductor per volt of potential difference between them. In this parallel-plate capacitor, where the conductors are metal plates, $C = q/v$. This capacitance can also be calculated (approximately) by the formula: $C = \kappa\varepsilon_0 A/d$.
A is the area (sq. meters) of each plate.
d is the distance (meters) between plates.
κ is the dielectric constant (nearly 1 for air, exactly 1 for vacuum, 7 or more for flint glass).
ε_0 is the 'permittivity of vacuum', it is equal to $10^7/4\pi c^2$
where c is the speed of light.

The closer the plates are together and the larger their area, the more accurate the formula becomes.

Another way to describe a capacitor is by its behavior when an alternating voltage is applied across its terminals.



This behavior is summarized in the graphs below (which might be displayed on an oscilloscope screen), showing how the current through a capacitor (dotted graph) and the voltage across it (solid graph) vary with time.



It is characteristic of a pure capacitor that the current wave is one-quarter cycle ahead of the voltage wave. The peak voltage divided by the peak current is the impedance of the capacitor. The impedance depends on the capacitance C (in farads) and on the frequency f (in hertz) of the alternating voltage: impedance of capacitor = $1/2\pi fC$ ohms.

HOW THE SPEED OF LIGHT GOT MIXED UP WITH CAPACITANCE

To those not deeply immersed in electrical matters, it may seem more than a little farfetched that the speed of light pops up in the calculation of a capacitance.

The paradox is at least partially resolved by recalling that light, after all, is an electromagnetic wave and its speed depends on basic characteristics of electric and magnetic fields.

In a little more detail, one notes that an electric charge can manifest itself in two ways:

- It is repelled by like charges and attracted by opposite ones.
- A moving charge is, in addition, acted on by other moving charges through the forces we call magnetic.

It turns out that the speed of light depends on the relative strength of these two effects—electrostatic attraction or repulsion on the one hand, and magnetic forces due to moving charges on the other.

And capacitance—in farads—depends on the same two effects:

1) Capacitance in farads is the number of coulombs needed to raise the p.d. of the capacitor to 1 volt. But the coulomb is the charge delivered by a current of 1 ampere in 1 second, and the ampere is defined in terms of *magnetic* forces between moving charges (See definition on page 269).

2) The p.d. is a measure of the energy per coulomb (1 volt=1 joule per coulomb) stored in the capacitor—energy that depends solely on the *electrostatic* attraction between the charges on the capacitor's two plates.

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tors well over 100,000,000 times larger. And they do this without noticeably increasing the uncertainty of the result—a measurement feat that is believed unique to the field of electricity. (For a comparable achievement in measuring length, one would have to measure a distance equal to that between New York and San Francisco by means of a measuring rod only 2 cm long, and do it without making any detectable error in the measurement process itself.)

The intercomparisons are made in a series of 10-to-1 stages: for example, a 10 pF capacitor is measured against a 1 pF capacitor, then a 100 pF capacitor is compared with the 10 pF one, and so on up the scale. This same technique has since been adapted to comparing standards of the volt and the ohm.

Better Farads, Ohms, and Amperes

Thanks to the calculable capacitor, the U.S. legal farad is believed to conform to the definition of the SI farad to within 0.02 ppm. (This, like other accuracy figures in this article, given in ppm, are estimated at the 95 percent confidence level).

Capacitors are critical components in all sorts of electronic circuits—amplifiers, oscillators, filters, pulse generators, and a hundred others. Tuning a radio or TV set, for example, is usually done by adjusting a variable capacitor. Considerably greater demands on accuracy are made in such applications as aircraft fuel gages and operational amplifiers for analog computers and control devices. The higher accuracy of the new capacitance standards makes quality control a lot easier for those who make precision capacitors and the instrumentation for measuring them.

The calculable capacitor is leading to more accurate standards of electrical resistance (the ohm) where high accuracy is in even greater demand. The ohm formerly was determined by comparison with a calculable inductor. One either calculated the inductance of a carefully designed coil from its dimensions and number of turns, or the mutual inductance of a pair of coils. Calculable capacitors have at least two advantages over calculable inductors: they are more easily shielded from external disturbances and their geometry is much simpler.

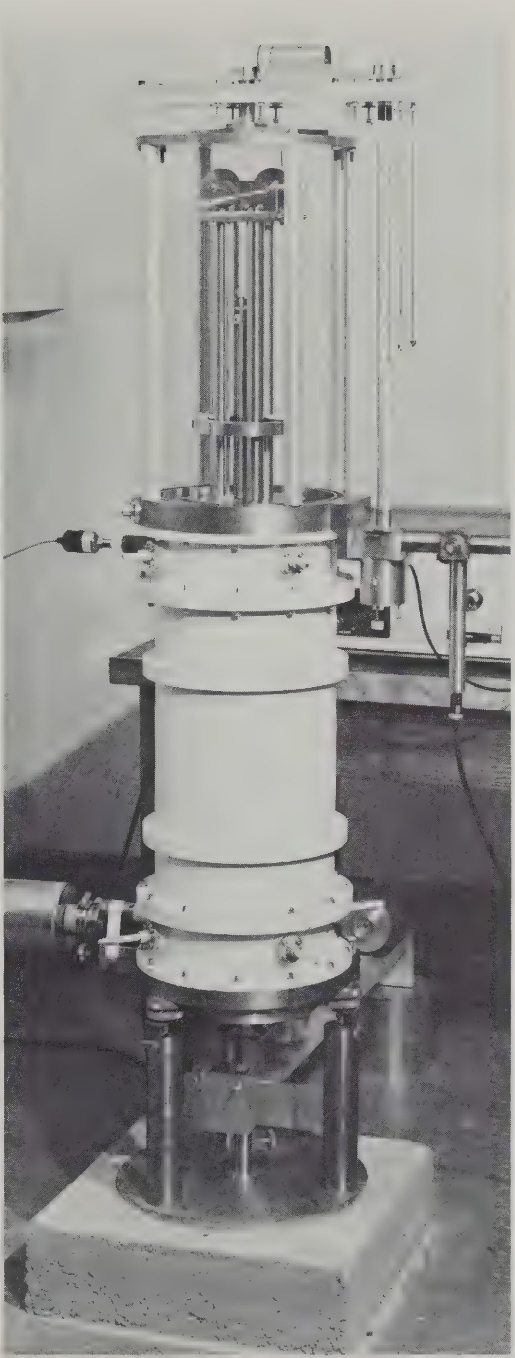
The calculable capacitor, jointly with the Josephson effect devices that are used in maintaining the U.S. legal volt, can also monitor the constancy of the effective ampere standard. Briefly: the calculable capacitor can reproduce the ohm with an uncertainty of 0.06 ppm (and prospects are good for doing even better); and the U.S. legal volt is reproducible with an uncertainty of 0.08 ppm. But standards of the ohm and volt, by way of Ohm's law, give us a corresponding ampere that can be reproduced with essentially the same relatively small uncertainty as the ohm. Our best procedure for the absolute determination of the ampere, which uses a current balance, has an uncertainty of about 15 ppm. Thus, although the ampere standard could conceivably vary, from one absolute determination to another, by as much as 15 ppm, scientists can nevertheless (through the ohm and volt standards) narrow the range of possible fluctuations in the U.S. legal ampere to less than 1/200 of that amount.

Calculable Capacitors

There were calculable capacitors before 1956, but achieving the required accuracy was so difficult that it discouraged their use as standards. Almost any physics textbook tells how to calculate the capacitance of a "parallel plate" capacitor—two equal metal disks, parallel to one another and separated by air or some other nonconductor. Unfortunately, the calculation is exact only under certain ideal conditions, and the capacitance is extremely sensitive to even very slight deviations from those conditions.

The merit of the cross capacitor is

continued on page 286



NBS calculable capacitor (variable cross capacitor) with upper cylindrical cover removed, showing pulley arrangement for raising and lowering the shield rod.

Using Computer Simulation to Solve Problems

SIMULATION, the use of a computer to implement mathematical or logical models for observing the behavior of a system, is one of the most consistently useful and productive applications of computer science.

Simulation has been employed widely in industry, academic institutions, and government for almost as long as the modern digital computer has been used. This application of the computer has been solving problems in the aerospace, chemical, and engineering areas for more than a quarter of a century, and is now moving into social science and management applications.

The National Bureau of Standards has used simulation models to substitute for actual experimentation in solving "real world" problems. The Bureau's Institute for Computer Sciences and Technology (ICST) has used simulation to determine the appropriateness of computer configurations for export control and to detail certain computer requirements of the Navy as part of a performance evaluation project.

Paul F. Roth, a computer specialist with ICST, has been engaged in many aspects of simulation since 1955. Before joining the Bureau, Roth spent 10 years in the aerospace industry performing simulation of aerospace systems, and then worked 6 years in the computer industry where he developed a simulation language used in predicting the performance of a manufacturer's computer line.

According to Roth, simulation is a multidisciplinary technology comprising elements of mathematics, engineering, and management science. He believes that the characteristics of simulation make it an excellent methodology for use in constructing models of systems whose states change with time and which may be too complex to be described by conventional mathematical systems. These models are implemented on a computer so that the machine can process the changes that would take place in the real world, generate statistics, and display the data.

The various types of simulations presently used are classified according to the nature of the systems they represent, with two of the most widely used classifications being *continuous event simulation* and *discrete event simulation.**

Continuous event or analog simulation, which preceded discrete event simulation by about a decade, is used for systems whose states change smoothly, such as the position of an airplane in flight. The changes in winds, the effect of control surfaces, and the altitude of the plane are examples of continuous variables in this system.

In discrete event simulation, the systems change states in abrupt steps. Roth cites the computer as a prime example of a discrete system due to its constant switching and changing of information states. A supermarket with its resource allocation and traffic pattern is another example of a typical discrete event system. Discrete event simulations focus on the users of the system who consume resources and expend time.

For the private sector, discrete event simulation in the modern sense began about 1959 with the development of job shop simulators by large industrial corporations to solve problems relating to the allocation and distribution of resources according to production scheduling. In 1962, the first general-purpose simulation languages, SIMSCRIPT and GPSS, were documented. The field of simulation grew from there, partially due to the increased speed of computers, the decreased cost of using them, and the development of powerful programming languages for simulation.

According to Roth, simulation gives the user the opportunity to study a real system and perform alternative modifications without actually changing the system. This is especially valuable in such areas as business policy and combat strategy where actual experimentation could be costly and/or disastrous. This computer experimentation can be done with a reasonable investment of time and money, especially where the system is not physically available for experimentation or where experimentation with the system is too dangerous. Simulation has been used to replace elements of systems or entire systems too large or cumbersome to test.

turn page

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* P. F. Roth, "Discrete Event Simulation," from *Encyclopedia of Computer Sciences*, by A. Ralston Petrocelli Publishers, to be published.

RAY 3300

One example of the use of simulation with such a system is in studying spacecraft docking, maneuvering, and re-entry. The calculations of the best angle of re-entry, for example, involve a variety of data such as the heat caused by atmospheric drag, orbital velocity, and aerodynamic characteristics. Using simulation, an engineer sitting at a terminal can change any one of these variables and determine almost immediately the impact of the change on vehicle performance.

Similarly, simulation has been used to study world weather dynamics and weapon effects.

In the business area, simulation can be used to improve a manufacturer's warehouse distribution system by helping him find the optimum number, size, and location of field warehouses needed for his product. The computer allows him to take into consideration simultaneously the manufacturing facilities, existing warehouses, transportation methods, production inventories, and the ultimate consumer, among other variables.

Another important use of this technique involves the simulation of traffic control systems for airports and airways.

In 1971, NBS used computer simulation to help the Federal Aviation Administration (FAA) upgrade part of its air traffic control system. Scientists from the Center for Computer Sciences and Technology (the forerunner of ICST) and the Applied Mathematics Division tested two types of plans for assigning flight identification codes to aircraft by simulating a representative sample of air traffic for a peak day.

Led by mathematician Judith Gilsinn, the Bureau also developed a simulation model of an airport terminal area for the FAA. The simulation, called DELCAP (for Delay/Capacity, the two items the simulation was designed to measure), is a planning and analysis tool for use in investigating factors affecting throughput (the number of operations handled by the facility per time period) and delay.

Input for the simulation included traffic levels, the mix and characteristics of aircraft types, the separation rules which apply, the airport runway configuration, and the runway operating policies. The simulation detailed those aspects on the flight of an aircraft which impede the free progress of other aircraft.

DELCAP was designed to answer questions such as "Can the present configuration at a given airport handle an increase of 50 percent in traffic?", and "Would delay be decreased by reserving one runway for large and medium size jets and large piston aircraft?" The simulation also examined the effects on congestion of adding extra runways.

In January 1975, the scientists published their modifications of the DELCAP simulation (originally produced in 1971) in order to allow more flexible sequencing of operations on runways handling landings and takeoffs. DELCAP has been run on O'Hare airport in Chicago, and New York's LaGuardia airport.

Bureau mathematicians have also used simulation to design a model describing the movement of trucks in lower Manhattan, contributing to a larger study by the Department of Housing and Urban Development. The study demonstrated how operations research and computer simulation techniques can assist urban planners.

Among the latest uses of computer simulation is, curiously, the prediction of the performance of computer systems themselves. According to Roth, a pioneer in the development of this specialized application of simulation, the technique can be used to test new computer designs and programs without the expense of full-scale construction and operation. Simulation can also solve problems dealing with the design of hardware and software configurations.

'76 SIMULATION CONFERENCE PLANNED

NBS plans to host the 1976 Winter Simulation Conference next December at the NBS Gaithersburg, Md. site. All major professional societies involved in simulation will join the National Bureau of Standards in sponsoring the Bicentennial event. The conference will cover a broad range of topics primarily related to discrete event simulation and modeling. For further information contact Paul Roth, Technology B240, NBS, Washington, D.C. 20234.

Paul F. Roth, a pioneer in the development of the specialized use of simulation to predict the performance of computer systems, has been involved in various aspects of simulation since 1955. For additional information about the 1976 Winter Simulation Conference, contact Roth in Room B256 Technology, NBS, Washington, D.C. 20234 phone (301) 921-3545.

For the past 3 years, ICST and the Association for Computing Machinery (ACM) have cosponsored the only conference devoted exclusively to the simulation of computer systems. This year's symposium, held in August at the NBS Boulder, Colo., laboratories, focused on the state of the art of this expanding field. According to Roth, originator and twice general chairman of the symposia, the meetings provide information on techniques of system model design, simulation languages, and software and hardware performance prediction, techniques which enable the design, procurement, and management of computers in a more cost-effective manner.

Today, a number of other symposia devoted to special applications of simulation are attracting new computer professionals to the field. Several major technical societies have simulation-oriented component organizations, such as the Special Interest Group on Simulation (SIGSIM) of the ACM.

Additionally, many universities are offering courses in simulation in an effort to foster the use of the technique in new and diverse areas. Roth periodically teaches graduate-level courses in simulation at the Virginia Polytechnic Institute and at the University of Maryland.

The applications of computer simulation in use by government and private institutions evidence it is a better way of solving problems. ☐

HIGHLIGHTS

New Technique for Fission Study

A research group at NBS has applied a powerful new tool to the study of nuclear fission. By inducing γ-ray fission and measuring the process to a sensitivity a million times greater than previously possible, the researchers have obtained results for the uranium isotope of mass 238. The technique can, it appears, be applied to all nuclei of interest for practical and scientific purposes.

The NBS work may prove useful in the effort to expand our national energy resources through the better understanding and use of nuclear fission. The new technique is reported in the September issue of The Physical Review C.

Videotape for Semiconductor Community

New and powerful applications for laser scanning in semiconductor device design and reliability work are presented in a videotape now available for distribution on loan without charge from NBS. Titled "Laser Scanning of Active Semiconductor Devices," the 55-minute presentation is given by David E. Sawyer and David W. Berning, developers of an optical scanner which can, in a completely nondestructive way, reveal the inner workings of semiconductor devices. As an added feature, Sawyer and Berning are available for a telephone conference call to answer questions and provide more detailed information following a prearranged showing of the videotape.

Persons wishing to borrow the videotape should contact Elaine C. Cohen, B346 Technology Building, NBS, Washington, D.C. 20234. The tape is available in color on ¾-inch cassettes and in black and white on ½-inch reels. An earlier videotape, titled "Defects in PN Junctions and MOS Capacitors Observed Using Thermally Stimulated Current and Capacitance Measurements," is also available on loan without charge.

Symposium on Micro and Mini Systems

A symposium on "Trends and Applications: Micro and Mini Systems" will be held at NBS, Gaithersburg, Md., May 27, 1976. The symposium will be sponsored by the IEEE Computer Society Eastern Area Committee, the Washington, D.C. Chapter, the IEEE Washington Section and NBS.

Submitted papers should be of a tutorial nature, describing practical experiences with micro and mini systems, or presenting new research results. Topics to be covered include: Networks of Processors, Multiprocessor Ensembles, Intelligent Terminals, Novel Architectures, Programming and Operating Systems, Security, Performance Evaluation, Novel Applications.

Three copies of 1,000 word abstracts should be submitted to: Jack Benoit, MITRE Corporation, Westgate Research Park, McLean, Va. 22101, by January 15, 1976. For further information, contact: Marshall Abrams, National Bureau of Standards, Technology B212, Washington, D.C. 20234, or call (301) 921-2601.

Computer Privacy Cost Model

A computerized model has been developed on an NBS contract to help Federal agencies implement the Privacy Act of 1974. The model, introduced at the Privacy Model Workshop for Federal Agencies held at NBS on October 3, 1975, is a tool for examining the cost of various technical and procedural alternatives for given systems of computerized records. By using the privacy model, proposed privacy safeguards can be examined for their cost impact before installation. Cost-effective alternatives can then be selected as necessary. Similarly, the privacy model can identify cost-savings resulting from the reduction or elimination of data collections.

The model will be available later this year through the National Technical Information Service. Inquiries about the privacy model should be addressed to: NBS Systems Architecture Section, Technology Building, A265, Washington, D.C. 20234.

Stronger Ceramics Through Better Design

NBS has conducted an error analysis on the equation used to develop design diagrams for structural ceramics. Since ceramics generally fail from pre-existing cracks, these diagrams are based on characterization of the behavior of cracks. Depending on the quality of the strength and crack growth data, NBS found an uncertainty in time-to-failure predictions of as much as 2 or 3 orders of magnitude. However, the error analysis also showed that a modest increase in the proof-test level or a modest decrease in the service load will offset the uncertainty.

Design techniques, such as those being developed at NBS for ceramics, are being used in a number of areas where structural reliability is of critical importance, including the design of space craft windows. ☐

Computer-Aided Manufacturing Can Increase Productivity

COMPUTER-aided manufacturing offers the opportunity to significantly increase National productivity and to reduce manufacturing costs, according to Dr. Betsy Ancker-Johnson, Assistant Secretary for Science and Technology of the Commerce Department.

Ancker-Johnson made these remarks at the Second International Computer-Aided Manufacturing (CAM) Standards Workshop held at the National Bureau of Standards.

The 3-day Workshop was sponsored by the NBS Institute for Computer Sciences and Technology and Computer-Aided Manufacturing-International, a non-profit organization dedicated to advancing the technologies of CAM. The meeting, attended by representatives of standards organizations working on various aspects of CAM, is designed to coordinate the activities of these groups and to begin development of a consensus CAM systems structure.

In her introductory remarks, Ancker-Johnson stressed that the subject of standards in CAM systems has significant potential for major economic impact. She cited examples of numerically controlled machine tools that have increased productivity by factors of three or four, and computer-aided design (CAD) systems that have demonstrated productivity increases by factors of six, seven, or more.

According to Ancker-Johnson, "In my view, computer-aided manufacturing in general, and the standardization of computer-aided manufacturing systems in particular, offer important opportunities for improvement in our technological situation, in our productivity growth, and in our international trade situation."

Many diverse companies and organizations are currently developing and implementing various components of computer-aided design and computer-aided manufacturing systems. Component parts of such systems come from the computer industry, the sensor and instrumentation industries, machine tool manufacturers, and materials handling systems manufacturers. Widespread and efficient applications of such systems will depend on the standard data base formats and computer languages and on standard interfaces between those various components.

Ancker-Johnson pointed out that the development of such standards and performance measures, to insure that all components fit together correctly and work satisfactorily, will improve the efficiency of capital investments.

The National Bureau of Standards is primarily concerned with standards for the interface specifications that allow all of the various modular components of manufacturing systems, both hardware and software, to fit together without expensive special engineering and computer programming. This concept is particularly important to medium and small firms which account for approximately three-fourths of the value of shipments in the discrete parts manufacturing industries. This conference is one important way that NBS is stimulating the development of such standards.

Keynote address for the workshop was presented by Thomas D. Morris, Assistant Comptroller General, U.S. General Accounting Office (GAO). Morris discussed the GAO study of CAD/CAM systems in the U.S. and foreign countries. The report, expected to be released in the near future, includes recommendations for government actions in the area of CAM to maintain this country's international trade position. □

Energy-Environment Workshops Planned

A series of workshops aimed at determining what kinds of standards may be needed for measuring environmental pollution associated with energy production is planned during the next 6 months by the National Bureau of Standards and the Environmental Protection Agency (EPA).

Beginning in January, workshops will be held at the National Bureau of Standards in Gaithersburg, Md., to determine how many and what kinds of Standard Reference Materials (SRM's) NBS should develop to assist EPA in measuring water and air pollution that may result from various types of energy production.

The workshops will focus on SRM needs for uranium mining, mine drainage, geothermal energy, power plant operation, and coal gasification, liquefaction,and desulfurization.

NBS SRM's are materials whose chemical composition or particular chemical or physical properties have been accurately determined and certified. More than 900 NBS SRM's are currently available and are used throughout industry and the scientific community to calibrate and evaluate measurement instruments and test methods.

The workshops are the first step in a 5-year program at NBS designed to meet the Nation's environmental measurement needs as alternative forms of energy are developed. Environmental information is needed to help regulatory officials assess whether energy development is occurring with acceptable environmental impact. The program, funded by EPA, is administered jointly by the EPA Office of Energy, Minerals, and Industry within the agency's Office of Research and Development and the NBS Office of Air and Water Measurement.

The schedule for the workshops is:

January 20, 21—SRM's for Coal Gasification and Liquefaction

February 3, 4—SRM's for Coal Desulfurization

February 19, 20—SRM's for Power Plant Operation

March 22, 23—SRM's for Uranium Mining

April 28, 29—SRM's for Mine Drainage

May 24, 25—SRM's for Geothermal Energy Utilization

A workshop on SRM's for offshore drilling was held on October 6 and 7 in Santa Barbara, Calif. A second workshop on SRM's for oil shale processing was held November 24 and 25 at NBS.

Attendance at the workshops is by invitation only. Proceedings will be published. Persons interested in obtaining more information should contact Donald Becker, NBS Energy-Environment Workshop Coordinator, Analytical Chemistry Division, Chemistry Building A309, Washington, D.C. 20234, (301) 921-2128. □

NBS Guides Consumers in Use of Color

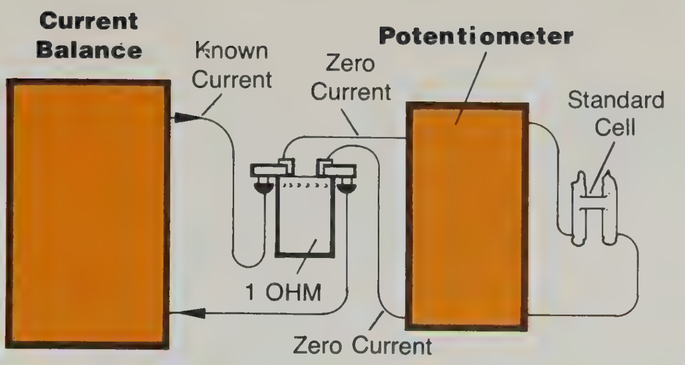
USING color to one's own best advantage is an art and a science. Both aspects are expertly analyzed in *Color in Our Daily Lives,* a booklet just published by the National Bureau of Standards.

The four-color, 32-page illustrated booklet—No. 6 in the NBS Consumer Information Series—takes the reader step by step through the fundamental principles of color and light, families of color, influence of colors upon others colors, and color harmony. It then discusses practical applications in sections on:

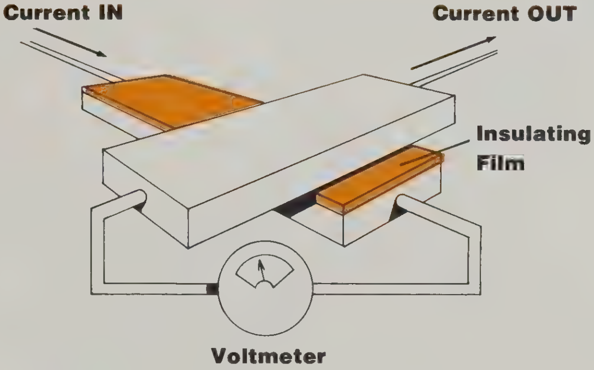
- Your Personal Color Plan
- Your Color Environment
- Color and Illumination
- Use Color to Dramatize or to Hide
- Color Plans for the Home
- Experimenting with Color.

Authored by the late Deane B. Judd, *Color in Our Daily Lives* reflects the wisdom and scientific insight attained by Dr. Judd in his 42-year research career at the Bureau. An internationally recognized expert, Judd, in this valedictory work, translated his basic color concepts into popular language for the ordinary consumer.

Color in Our Daily Lives, NBS Consumer Information Series No. 6, is available from the U.S. Government Printing Office at $1.70 a copy. Use Superintendent of Documents (SD) Catalog No. C13.53.6 when ordering. □



The voltage (V) of a standard cell in SI units is determined by comparing it with the voltage across a known resistance (R) through which a known current (I—the same current that is flowing through the coils of a current balance), using Ohm's law: V = I•R.



a.c. Josephson effect, as used in maintaining the constancy of the U.S. legal volt. Microwaves of fixed, accurately known frequency irradiate the junction of two superconductors (the temperature is near absolute zero) separated by a thin non-conducting film. If current is increased steadily from zero, voltage remains zero until a critical current, when the voltage jumps to △ v, a small value determined by the microwave frequency. At a somewhat larger current, the volage rises suddenly to 2•△ v, and so on—rising in a series of equal steps. At any point, the voltage is some whole number of times △ v. By setting the current so that it is in the range where the voltage is some specified multiple, n•△v, we always obtain the same voltage, to a high degree of precision. This voltage is then compared with the voltages of the NBS standard cells.

Electrical *continued*

standards) in a carefully stabilized environment. The resistances of these standards were originally determined by comparing them with a calculable *inductor*. However, preliminary comparisons have now been made with reference capacitors that, in turn, were compared with the calculable capacitor. As a result, the value of the U.S. legal ohm is believed known, in terms of the SI ohm, to within 0.06 ppm.

Inductance: the henry

It has not been found necessary to maintain a physical embodiment of the *henry*, SI unit of inductance. NBS calibrates precision inductors by comparing them, in a special a.c. bridge, with known capacitors and resistors.

Current: the ampere

The SI definition of the ampere, quoted above, is not, as one soon notices, directly applicable because of its reference to infinite conductors. But when we interpret it in the context of electrical theory we can deduce certain relations that *are* applicable. We can, for example, work out the relation between the magnetic force between two coils and the current flowing in them (the same current in each coil) when we know the size, shape, number of turns and relative placement of the coils. By measuring the force between two such coils—an instrument for doing this is called a "current balance"—we can calculate the current flowing in them, expressed in the same amperes that are described in the SI definition.

An absolute determination of the ampere by means of a current balance is undertaken by NBS about every 10 years. During each such experiment, which makes the standard current available for about 15 minutes, the value of the current in amperes can be determined to within about 15 ppm.

Electromotive force/potential difference: the volt

During the few minutes the current is flowing in the current balance, it also passes through some known resistances. Using Ohm's law, the potential drop across each resistor can be calculated and can at the same time be used to calibrate the emf of a standard voltage cell.

The accuracy of volt standards calibrated in this way is limited by the uncertainty (15 ppm) in the ampere. Volt standards can, however, be compared with one another to within 0.02 ppm. The U.S. legal volt is based on the average of a set of standard cells (saturated Weston cells) whose voltages are assigned (and monitored about once a month) by an a.c. Josephson effect device, a precise and linear voltage-to-frequency converter. The U.S. legal volt is believed constant to within 0.08 ppm, though it could conceivably differ from the SI volt by as much as 15 ppm.

To sum up, NBS has highly accurate standards of the farad and ohm. The standards of ampere and volt are somewhat less accurate (1 part in 66,000). However, by means of the Josephson effect, NBS can assure the constancy of its volt standards within extremely narrow limits (±0.08 ppm). Since the ohm is so accurately known, any improvement in the accuracy of either the ampere or the volt can immediately be transferred to the other (using Ohm's law). The main problem now facing electrical metrologists, therefore, is how to increase the accuracy of the volt or ampere standards, hopefully to match the high level of constancy made possible by the Josephson effect. ☐

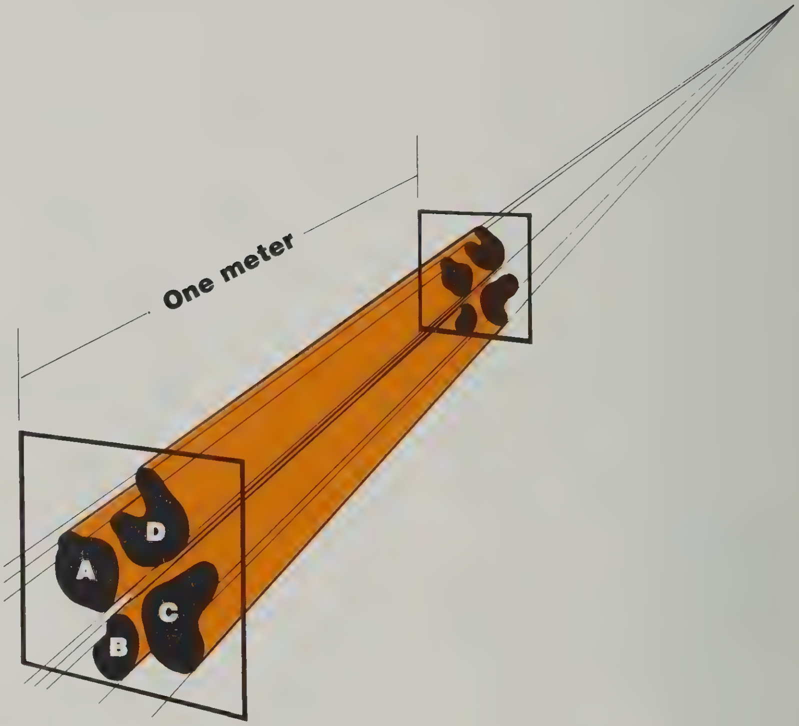
that it does not suffer from this undesirable hypersensitivity. Basically, a cross capacitor is *two* capacitors; the calculated capacitance is the average of the two. And the two capacitors are so related that a misalignment or misplacement of any of the critical parts gives rise to two opposing effects: It increases one of the capacitances and simultaneously decreases the other by nearly the same amount.

The Thompson-Lampard Theorem

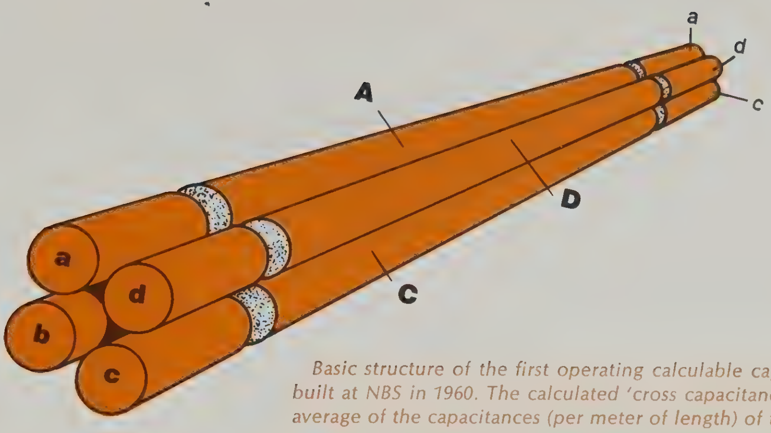
The kind of situation considered in the Thompson-Lampard theorem, on which the calculable capacitor is based, is not difficult to describe: a set of four metal rods—call them A, B, C and D—of indefinite length and placed parallel and close to one another, as suggested in the illustration. The cross section of any one rod is uniform along its length, but different rods can have different cross sections.

Now any two conductors, say portions of rods A and C, separated by a nonconductor (air, for example) constitute a capacitor. But because the rods are "indefinite" in length, we can only speak of their capacitors per unit length. Suppose, then, the A-C rod pair has a capacitance of C_1 farads per meter while the capacitance of rod pair B-D is C_2 farads per meter. Also, let $\overline{C}$ be the average of C_1 and C_2.

Then the Thompson-Lampard theorem leads to this remarkable result: If C_1 and C_2 are nearly equal, then we can not only calculate the value of $\overline{C}$, but the calculated value is—to a very high degree of accuracy—the *same* for all sets of rods that satisfy this condition. This constant value of $\overline{C}$ is about 2 picofarads per meter.



The Thompson-Lampard theorem, which led to the calculable capacitor, deals with four infinitely long, parallel conducting rods, each of uniform but arbitary cross section. In this perspective schematic sketch, two cross sections (black areas) are indicated, and the rods are to be thought of as continuing indefinitely to the front and rear.



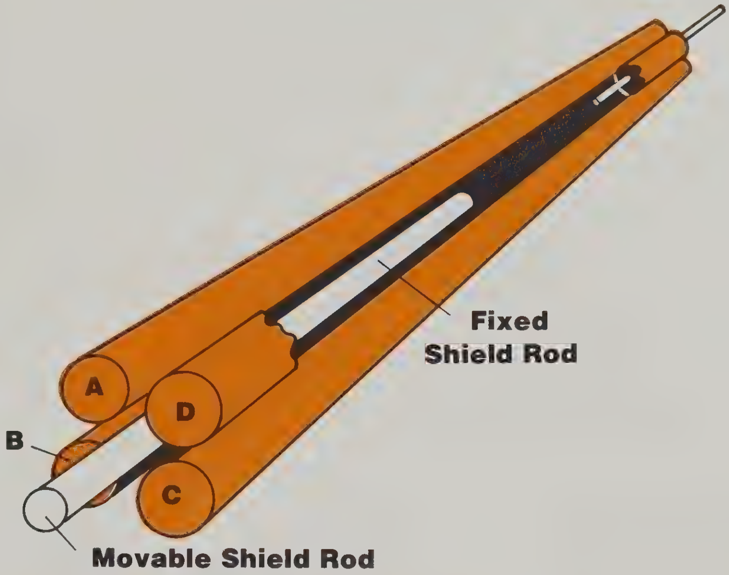
Basic structure of the first operating calculable capacitor, built at NBS in 1960. The calculated 'cross capacitance' is the average of the capacitances (per meter of length) of the capacitor formed by rods A and C and that formed by B and D. When the 'guard' sections a, a are kept at the same voltage as A, b, b at the same voltage as B, etc., then A, B, C and D act very nearly as if parts of infinitely long rods.

From Fixed to Variable

In practice, of course, rods of definite length must be used. But by placing a "guard section" near either end of each rod (insulated from, but kept at the same potential as, the rod) it can be made to behave much as if it were part of an infinitely long rod. Also, it is easiest to use four rods of the same circular cross section, with the centers at the corners of a square. A "grounded" metal cylinder, enclosing the entire cross capacitor, is employed to shield it from electrostatic fields between itself and conductors in the vicinity.

The first operating calculable capacitor of this kind was built in 1960 by Robert D. Cutkosky at NBS. Its electrodes (rods) were precision gage blocks, and it was used to calibrate an ohm standard to 6 ppm. Cutkosky also extended the theory to allow for nonconducting films on the electrodes.

An important change came in 1964 when Thompson and Lampard, working with W. K. Clothier, made the cross capacitor variable. They did this by inserting a grounded rod down along the central axis of the device. This acts as a shield between opposite rods, reducing C_1 and C_2 effectively to zero over the distance the shield rod has been inserted. The A-C and B-D capacitances are again restored as the movable rod is withdrawn. Leaving out the complicated details, if the rod is pulled out through a distance L, the cross capacitance increases by L•C. Clothier built an instrument of this design in 1964. Its accuracy was limited to about 0.5 ppm by the then existing uncertainty in the speed of light.



Basic structure of the variable cross capacitor used as standard of farad and ohm. The capacitance calculated is the change in cross capacitance when the movable shield rod is displaced through a measured distance along the axis. (Most of rod D has been removed so the shield rod can be better seen. Note that the variable cross capacitor does not need guard sections. Omitted from this and the preceding figure is the metal shield that encloses the entire device).

The second cross capacitor at NBS was of this variable kind. It was built by Cutkosky in 1974 and is the one used by him to determine the farad to 0.02 ppm and the ohm to 0.06 ppm. Besides the advantages inherent in the variable cross capacitor, plus some refinements worked out at NBS, this cross capacitor has the major advantage arising from the use of a stabilized laser for the interferometric measurement of the displacement L.

Thus in less than twenty years the calculable capacitor has become one of the two pillars of the electrical measurement system (the other is the ac. Josephson effect) that are primarily responsible for the accuracy and stability of that system. ☐

Index To

DIMENSIONS NBS

Volume 59, 1975

A-B

A Look at the Ozone Problem (May) 108
A New Look at the View From Within (Aug.) 174
Accelerator Facilities Upgraded, Particle (Mar.) 68
Accelerometers Determined, Effects on Piezoelectric (Apr.) 88
Air Conditioners, Check Energy Labels on Room (June) 138
Air Conditioners Save Energy, Money, New (July) 164
Air Pollution Standards Developed by NBS, New (May) 102
Air, There's More to Comfort Than Hot (Apr.) 78
Analysis for Silicon Devices, Surface (Aug.) 188
An International Meeting, A Century Celebration (Oct.) 224
Appliance Manufacturers Support Energy Efficiency Program, Major (June) 137
APT Programming Language, Standards for (July) 165
1975 Arrived Late (Feb.) 40
Assessing the Hazard Potential of Chemical Substances (Feb.) 34
Auto Fuels, Measuring Lead in (Aug.) 190
Banking the Environment (July) 147
Basis of the U.S. National Measurement System in Electricity (Dec.) 267
Beyond X-Rays (May) 106
Bone "Cement" Characterized (June) 136
Bridges, NBS Tests Epoxies to Protect (Apr.) 83
Building Construction to be Held at NBS, Workshop Underway, Symposium on (Oct.) 233
Building, Natural Hazard Evaluation of Existing (Apr.) 92
Buses, Subway Cars for Fire Safety, NBS Tests (July) 154

C-D

Calculable Capacitor, The Rise of the (Dec.) 274
Call for Papers Issued for NBS/ANSI Symposium (May) 65
Camera Guidelines to Help Cut Thefts, Surveillance (May) 114
Camera Keeps Eye on Nuclear Fuels, NBS (Jan.) 6
Cars for Fire Safety, NBS Tests Buses, Subway (July) 154
Celebrating the Treaty of the Metre 1875-1975 (May) 104
"Cement:" Characterized, Bone (June) 136
Centennial Volume Published (July) 161
Check Energy Labels on Room Air Conditioners (June) 138
Chemical Substances, Assessing the Hazard Potential of (Feb.) 34
Codes and Controls, New Standards for Computer (Apr.) 90
Color, NBS Guides Consumers in Use of (Dec.) 284
Communication, Safer Streets Through Improved (Mar.) 54
Communications, NBS Tests 'Little Box' That Speeds Police (May) 115
Computer-Aided Manufacturing Can Increase National Productivity (Dec.) 283
Computer and Our Society in the Next Two Decades, You, the (June) 131
Computer Codes and Controls, New Standards for (Apr.) 90
Computer Networks Are Here (Apr.) 75
Computer Program Announced (Sept.) 212
Computer Security Published, Guidelines for (Nov.) 259
Computer Simulation to Solve Problems, Using (Dec.) 278
Computer Symposium Planned (July) 163
Computer Users, New Flowchart Template for Federal (Mar.) 65
Computerized Elections, NBS Proposes Guidelines for (May) 99
Computers and Copyrights, NBS to Study (Apr.) 89
Computers Automate Jet Engine Tuneups (Jan.) 3
Conductivity Discussed, Thermal (Sept.) 211
Consumer Programs, NBS Strengthens (Jan.) 20
Consumers, Energy Labeling Explained for (Sept.) 210
Consumers in Use of Color, NBS Guides (Dec.) 284
Conversion Submitted to Congress, Revised Bill for Voluntary Metric (Apr.) 91
Copyrights, NBS to Study Computers and (Apr.) 89
Court Records, Guidelines for Keeping Better (Mar.) 56
Crime Labs Aided by NBS Glass Standard (Jan.) 8
Cryogenic Fluid Safety Data Compiled (Sept.) 208
Cryptography, Data Protection Through (Sept.) 195
Data Available, Ethane (July) 164
Data Compiled, Cryogenic Fluid Safety (Sept.) 208
Data on Household Fires, Survey Results in New (Jan.) 10
Data on Methane, New (Mar.) 67
Data Protection Through Cryptography (Sept.) 195
Dental Filling Materials, Instrument Evaluates Wear of (May) 112
Determining the Effect of Weather on Building Materials (Sept.) 198
Dew/Frost Detector, NBS Three in the I-R 100: Radiometer, Laser Stabilizer, (Nov.) 256
Dry Weight, New Technique in Predicting (Oct.) 235
Durability Studied, Mobile Home Safety, (June) 133

E-F-G

Ears or Don't Shoot, Now Hear This! Protect Your (Oct.) 219
Effects on Piezoelectric Accelerometers Determined (Apr.) 88
Elections, NBS Proposes Guidelines for Computerized (May) 99
Electric Power Networks for Dollar Savings and Quality Control, Monitoring (July) 152
Electricity, Basis of the U.S. National Measurement System in (Dec.) 267
Electrocatalysis Processes, NBS Workshops to Study (Nov.) 260
Energy Conservation Dollars, NBS, FEA Help Homeowners Make the Most of Their (Feb.) 27
Energy Dollars, Making the Most of Your (Aug.) 180
Energy Efficiency Program, Fifty-Seven Major Appliance Manufacturers Support (Nov.) 258
Elusive Pulses Measured (Oct.) 234
Energy Efficiency Program, Major Appliance Manufacturers Support (June) 137
Energy-Efficient Water Heaters to Save Money (Aug.) 189
Energy-Environment Workshops Planned (Dec.) 284
Energy Labeling Explained for Consumers (Sept.) 210
Energy Labels on Room Air Conditioners, Check (June) 138
Energy, Money, Air Conditioners Save (July) 164
Energy Needs: Newest Challenge to Yankee Ingenuity (Sept.) 204
Energy R&D, NBS, ERDA Sign Agreement on (Oct.) 236
Energy Research: The Long-Term Perspective (Jan.) 12

Energy Strategies for Health Care Institutions (Oct.) ... 222
Engine Tuneups, Computers Automate Jet (Jan.) ... 3
Environment, Banking the (July) ... 147
Epoxies to Protect Bridges, NBS Tests (Apr.) ... 83
Equipment, Facilities for Shared Use (July) ... 162
Equipment, Safety of Playground (Feb.) ... 36
ERDA Sign Agreement on Energy R&D, NBS, (Oct.) ... 236
Estimating Gas Consumption (Feb.) ... 30
Ethylene Study, NBS, Industry to Join (Jan.) ... 20
ETIP, Utility Commissions and Policy Experiments (May) 112
Ethane Data Available (July) ... 164
Evaluation of Existing Building, Natural Hazard (Apr.) ... 92
Evidence, Toward More Objective (Mar.) ... 59
Facilities for Shared Use, Equipment, (July) ... 162
Facts on High Rise Fires (Feb.) ... 42
Fatalities, New Insights on the Causes of Fire (June) ... 126
Fifty Glass Standard Reference Materials Available (Feb.) 41
Fifty-Seven Major Appliance Manufacturers Support Energy Efficiency Program (Nov.) ... 258
Fire Fatalities, New Insights on the Causes of (June) ... 126
Fire Research Programs Outlined (July) ... 163
Fire Safety for New Subway in Nation's Capital (Dec.) . 272
Fire Safety, NBS Tests Buses, Subway Cars for (July) ... 154
Fire Safety Research Symposium Available, Proceedings of (Mar.) ... 66
Fires, Facts on High Rise (Feb.) ... 42
Fires, Survey Results in New Data on Household (Jan.). 10
Flammability Standard for Sleepwear, New (Jan.) ... 21
Fluid Safety Data Compiled, Cryogenic (Sept.) ... 208
Fluorides and Sealants: Stopping Cavities Before They Start (Nov.) ... 253
Fuel Topics Published, Hydrogen (June) ... 138
Fuels, Measuring Lead in Auto (Aug.) ... 190
Fuels, NBS Camera Keeps Eye on Nuclear (Jan.) ... 6
Gas Consumption, Estimating (Feb.) ... 30
Glass Standard, Crime Labs Aided by NBS (Jan.) ... 8
Glass Standard Reference Materials Available, Fifty (Feb.) ... 41
Good Science, Bad Data (Feb.) ... 32
Graffiti, NBS Studies Ways to Prevent and Remove (July) 150
GSA Experiment for Savings and Product Improvement, NBS, (Sept.) ... 210
Guidelines for Computer Security Published (Nov.) ... 259
Guidelines for Computerized Elections, NBS Proposes (May) ... 99
Guidelines for Keeping Better Court Records (Mar.) ... 56

H-I

Harnessing the Sun (Apr.) ... 84
Hazard Evaluation of Existing Building, Natural (Apr.) . 92
Hazard Potential of Chemical Substances, Assessing the (Feb.) ... 34
Health Care Delivery in Hospitals Being Aided (Oct.) ... 232
Health Care Institutions, Energy Strategies for (Oct.) ... 222
Heat Pump in Your Future? Is There a (Nov.) ... 244
Heat with Improved Reliability, Pacing (Nov.) ... 250
Heaters to Save Money, Energy-Efficient Water (Aug.). 189
Helping Improve Police Protection (Mar.) ... 58
High Rise Fires, Facts on (Feb.) ... 42
HIGHLIGHTS
  Agreement with Nuclear Regulatory Commission (Nov.) ... 255
  Air Pollution Measured (Apr.) ... 87
  Atmospheric Chemistry Publication (Oct.) ... 230
  Atomic Clock Now Portable (Nov.) ... 255
  Automated Acoustic Measurements (Apr.) ... 87
  Biological Molecules Program (Aug.) ... 187
  Biomaterials Publication (Sept.) ... 207
  Booklets on Major Issues (Aug.) ... 187
  Checking Bike Forks (Jan.) ... 16
  Clinical Standards (July) ... 160
  CODATA Conference (Oct.) ... 230
  Computer Networking (May) ... 111
  Computer Privacy Cost Model (Dec.) ... 282
  Consumer Information (July) ... 160
  Consumer Sounding Boards (Aug.) ... 187
  Crystal Data on Magnetic Tape (Sept.) ... 207
  Data Elements Symposium (Aug.) ... 187
  Data Privacy Symposium (Mar.) ... 64
  Design Concepts (May) ... 111
  Director Leaves for ERDA (July) ... 160
  Disk Calibration Service (Apr.) ... 87
  Energy Conservation Pamphlets in Spanish (July) ... 160
  Energy-Related Inventions (Mar.) ... 64
  Environmental Specimen Bank (May) ... 111
  Environmental Standards (June) ... 135
  Fire Control Act (Jan.) ... 16
  Fossil Fuel Standards (Jan.) ... 16
  Gas Cylinder Specifications (Feb.) ... 39
  Gaseous Fuels (May) ... 111
  High Wind Film (Aug.) ... 187
  Highest Frequency Measurements (Feb.) ... 39
  Home Playground Equipment (Apr.) ... 87
  International MHD Conference (Apr.) ... 87
  Laboratory Thermometers (May) ... 111
  Laser Power Meter (Feb.) ... 39
  Lead in Reference Fuel (June) ... 135
  Lead Paint Survey Completed (Sept.) ... 207
  Louisiana and Montana Receive Standards (July) ... 160
  Magnification SRM (Oct.) ... 230
  Marine Pollution Monitoring (Apr.) ... 87
  Measuring Water/Air Pollution (Mar.) ... 64
  Metric Conference (Apr.) ... 87
  Metric Conversion (July) ... 160
  Metric Slide Show (Mar.) ... 64
  Micro and Mini Systems Symposium (Dec.) ... 282
  Mobile Home Projects (Feb.) ... 39
  More on Appliance Efficiency (Feb.) ... 39
  NBS Annual Report (June) ... 135
  NBS/BRH Teletherapy-Dosimetry (Jan.) ... 16
  NBS/NIH Agreement (Nov.) ... 255
  NBS Mercury Dosimeter (Nov.) ... 255
  NBS to Exhibit Calibration System (Mar.) ... 64
  Neutron Radiography Program (Aug.) ... 187
  New Energy Guide Labels (Oct.) ... 230
  New Environmental Standard (Mar.) ... 64
  New Fire Test Enclosure (Sept.) ... 207
  New Glass SRM Issued (Aug.) ... 187
  New Josephson Device (Feb.) ... 39
  New Miniature Temperature Probe (Nov.) ... 255
  New Publication on Nuclear Theory (July) ... 160
  New SRM Catalog (Sept.) ... 207

turn page

Index *continued*

  New Technique for Fission Study (Dec.) 282
  New Standard for Cobol-74 (Nov.) 255
  New Structured Programming Language (Mar.) 64
  New Voluntary Standard (Sept.) 207
  Noise-Con 75 (June) 135
  Optical Character Recognition (Feb.) 39
  Pacemaker Workshop at NBS (Sept.) 207
  Performance Criteria (May) 111
  Piezoelectric Effect in Bone and Teeth (Nov.) 255
  Portable X-Ray Devices (June) 135
  Radiation Safety Standard (May) 111
  Residual Oil SRM (Oct.) 230
  Roofing Conference (Feb.) 39
  Software Engineering Handbook (Jan.) 16
  Solar Heating and Cooling Costs (Sept.) 207
  Standards for Handcuffs (Jan.) 16
  Stronger Ceramics Through Better Design (Dec.) 282
  SURF 2 is Up (Feb.) 39
  Testing Gypsum Wallboard (Mar.) 64
  Transformation of Cadmium (Oct.) 230
  Triple-Point Vapor Pressure of Water (June) 135
  Videotape for Semiconductor Community (Dec.) 282
  Weather Service Network (June) 135
  Windows and People (Jan.) 16
Highway Safety, NBS Brightens the Way for (Aug.) 178
Homeowners Make the Most of Their Energy Conservation Dollars, NBS, FEA (Feb.) 27
Hospitals Being Aided, Health Care Delivery in (Oct.). 232
Hot Air, There's More to Comfort Than (Apr.) 78
Hydrogen Fuel Topics Published (June) 138
Information as a Resource, Managing (Apr.) 88
Instrument Evaluates Wear of Dental Filling Materials (May) 112
Investigating the Performance of Security Systems (Mar.) 60
Isotopes, Laser-Induced Photochemical Enrichment of (Apr.) 80
Is There a Heat Pump in Your Future? (Nov.) 244

L-M-N

Labeling Explained for Consumers, Energy (Sept.) 210
Labels on Room Air Conditioners, Check Energy (June) 138
Labs Aided by NBS Glass Standard, Crime (Jan.) 8
Laser-Induced Photochemical Enrichment of Isotopes (Apr.) 80
Laser Stabilizer, Dew/Frost Detector, NBS Three in the I-R 100: Radiometer, (Nov.) 256
Law Enforcement Standards Laboratory, The (Mar.) 51
Lead in Auto Fuels, Measuring (Aug.) 190
Magnetohydrodynamics—An Old Idea with More Power to It (June) 128
Major Appliance Manufacturers Support Energy Efficiency Program (June) 137
Making the Most of Your Energy Dollars (Aug.) 180
Managing Information as a Resource (Apr.) 88
Materials Available, Fifty Glass Standard Reference (Feb.) 41
Materials, Determining the Effect of Weather on Building (Sept.) 198
Measurement Science, World Conference Updates Vocabulary of (Oct.) 225
Measurement Seminars, NBS to Hold (Jan.) 17
Measurement System in Electricity, Basis of the U.S. National (Dec.) 267
Measuring Lead in Auto Fuels (Aug.) 190
Mercury Standards Will Aid Water Pollution Studies, New NBS (May) 116
Methane, New Data on (Mar.) 67
Metre 1875-1975, Celebrating the Treaty of the (May) 104
Metric Changeover, More on the (June) 123
Metric Conversion Submitted to Congress, Revised Bill for Voluntary (Apr.) 91
Metric Kit Published (Mar.) 66
Metric, Survey Shows Schools Going (Jan.) 19
Metric Vocabulary: A Reference Guide (Oct.) 228
Mobile Home Safety, Durability Studied (June) 133
Monitoring Electric Power Networks for Dollar Savings and Quality Control (July) 152
More on the Metric Changeover (June) 123
Natural Hazard Evaluation of Existing Building (Apr.) 92
NBS/ANSI Symposium, Call for Papers Issued for (Mar.) 65
NBS Brightens the Way for Highway Safety (Aug.) 178
NBS Camera Keeps Eye on Nuclear Fuels (Jan.) 6
NBS Circulates Voluntary Toy Safety Standards (Nov.). 259
NBS, EPA to Offer Sound Level Meter Workshop (Oct.) 232
NBS, ERDA Sign Agreement on Energy R&D (Oct.) 236
NBS, FEA Help Homeowners Make the Most of Their Energy Conservation Dollars (Feb.) 27
NBS, GSA Experiment for Savings and Product Improvement (Sept.) 210
NBS Guides Consumers in Use of Color (Dec.) 284
NBS, Industry to Joint Ethylene Study (Jan.) 20
NBS Proposes Guidelines for Computerized Elections (May) 99
NBS Tests Epoxies to Protect Bridges (Apr.) 83
NBS Tests 'Little Box' That Speeds Police Communications (May) 115
NBS to Hold Measurement Seminars (Jan.) 17
NBS to Study Computers and Copyrights (Apr.) 89
NBS Strengthens Consumers Programs (Jan.) 20
NBS Studies Ways to Prevent and Remove Graffiti (July) 150
NBS Tests Buses, Subway Cars for Fire Safety (July) 154
NBS Tests Six-Axis Robot (Oct.) 231
NBS Three in the I-R 100: Radiometer, Laser Stabilizer, Dew/Frost Detector (Nov.) 256
NBS Workshops to Study Electrocatalysis Processes (Nov.) 260
Networks Are Here, Computer (Apr.) 75
New Air Conditioners Save Energy, Money (July) 164
New Air Pollution Standards Developed by NBS (May) 102
New Data on Methane (Mar.) 67
New Flammability Standard for Sleepwear (Jan.) 21
New Flowchart Template for Federal Computer Users (Mar.) 65
New Insights on the Causes of Fire Fatalities (June) 126
New NBS Mercury Standards Will Aid Water Pollution Studies (May) 116
New Standards for Computer Codes and Controls (Apr.) 90
New Technique in Predicting Dry Weight (Oct.) 235
New Time Rules (Feb.) 40
Now Hear This! Protect Your Ears on Don't Shoot (Oct.) 219
Nuclear Fuels, NBS Camera Keeps Eye on (Jan.) 6

O-P-Q

Optical Spectra Table Revised (Sept.) 209
Ozone Controversy, Research Provides New Insight into (Nov.) 247

Ozone Problem, A Look at the (May) 108
Pacing the Heart with Improved Reliability (Nov.) 250
Particle Accelerator Facilities Upgraded (Mar.) 68
Patrolcar Performance and Safety Studied (Mar.) 63
Performance and Safety Studied, Patrolcar (Mar.) 63
Performance of Security Systems, Investigating the (Mar.) 60
Photochemical Enrichment of Isotopes, Laser-Induced (Apr.) 80
Piezoelectric Accelerometers Determined, Effects on (Apr.) 88
Pipes, Pros and Cons, Plastic (Sept.) 202
Plastic Pipes, Pros and Cons (Sept.) 202
Police Communications, NBS Tests 'Little Box' That Speeds (May) 115
Police Protection, Helping Improve (Mar.) 58
Pollution Studies, New NBS Mercury Standards Will Aid Water (May) 116
Power Networks for Dollar Savings and Quality Control, Monitoring Electric (July) 152
Power to It, Magnetohydrodynamics—An Old Idea with More (June) 128
Pressure Transducer Service Available (Aug.) 190
Proceedings of Fire Safety Research Symposium Available (Mar.) 66
Product Improvement, NBS, GSA Experiment for Savings and (Sept.) 210
Product Standards for a Summer Afternoon (July) 156
Productivity, Computer-Aided Manufacturing Can Increase National, (Dec.) 283
Pulses Measured, Elusive (Oct.) 234

R-S-T

Radiometer, Laser Stabilizer, Dew/Frost Detector, NBS Three in the I-R 100: (Nov.) 256
Railway Safety, Working for (Aug.) 171
Records, Guidelines for Keeping Better Court (Mar.) 56
Research Programs Outlined, Fire (July) 163
Research Provides New Insight into Ozone Controversy (Nov.) 247
Research: The Long-Term Perspective, Energy (Jan.) 12
Resource, Managing Information as a (Apr.) 88
Revised Bill for Voluntary Metric Conversion Submitted to Congress (Apr.) 91
Robot, NBS Tests Six-Axis (Oct.) 231
Safer Streets Through Improved Communication (Mar.) 54
Safety Data Compiled, Cryogenic Fluid (Sept.) 208
Safety, Durability Studied, Mobile Home (June) 133
Safety for New Subway in Nation's Capitol, Fire (Dec.) 272
Safety, NBS Brightens the Way for Highway (Aug.) 178
Safety, NBS Tests Buses, Subway Cars for Fire (July) 154
Safety of Playground Equipment (Feb.) 36
Safety Research Symposium Available, Proceedings of Fire (Mar.) 66
Safety Studied, Patrolcar Performance and (Mar.) 63
Savings and Product Improvements, NBS, GSA Experiment for (Sept.) 210
Science, Bad Data, Good (Feb.) 32
Schools Going Metric, Survey Shows (Jan.) 19
Security Systems, Investigating the Performance of (Mar.) 60
Silicon Devices, Surface Analysis for (Aug.) 188
Sleepwear, New Flammability Standard for (Jan.) 21
Sound Level Meter Workshop, NBS, EPA to Offer (Oct.) 232
Spectra Table Revised, Optical (Sept.) 209
Standard, Crime Labs Aided by NBS Glass (Jan.) 8
Standards Developed by NBS, New Air Pollution (May) 102
Standards for APT Programming Language (July) 165
Standards for a Summer Afternoon, Product (July) 156
Standards for Computer Codes and Controls, New (Apr.) 90
Standards Laboratory, The Law Enforcement (Mar.) 51
Standards Will Aid Water Pollution Studies, New NBS Mercury (May) 116
Subway in Nation's Capital, Fire Safety for New (Dec.) 272
Sun, Harnessing the (Apr.) 84
Surface Analysis for Silicon Devices (Aug.) 188
Surface Finish of Silicon Devices, Workshop on (Feb.) 43
Surveillance Camera Guidelines to Help Cut Thefts (May) 114
Survey Results in New Data on Household Fires (Jan.) 10
Survey Shows Schools Going Metric (Jan.) 19
Symposium on Building Construction to be held at NBS, Workshop Underway (Oct.) 233
Symposium Planned, Computer (July) 163
System in Electricity, Basis of the U.S. National Measurement (Dec.) 267
Systems, Investigating the Performance of Security (Mar.) 60
Template for Federal Computer Users, New Flowchart (Mar.) 65
Thefts, Surveillance Camera Guidelines to Help Cut (May) 114
There's More to Comfort Than Hot Air (Apr.) 78
Thermal Conductivity Discussed (Sept.) 211
Time Rules, New (Feb.) 40
The Law Enforcement Standards Laboratory (Mar.) 51
The Rise of the Calculable Capacitor (Dec.) 274
Toward More Objective Evidence (Mar.) 59
Toy Safety Standards, NBS Circulates Voluntary (Nov.) 259
Transducer Service Available, Pressure (Aug.) 190
Treaty of the Metre 1875-1975, Celebrating the (May) 104

U-V-W

Using Computer Simulation to Solve Problems (Dec.) 278
Utility Commissions and Policy Experiments, ETIP (May) 112
View From Within, A New Look at the (Aug.) 174
Water Heaters to Save Money, Energy-Efficient (Aug.) 189
Water Pollution Studies, New NBS Mercury Standards Will Aid (May) 116
Wear of Dental Filling Materials, Instrument Evaluates (May) 112
Weather on Building Materials, Determining the Effect of (Sept.) 198
Weights and Measures, An International Meeting, A Century Celebration (Oct.) 224
Weights and Measures, World Conference Updates Vocabulary of Measurement Science (Oct.) 225
Working for Railway Safety (Aug.) 171
Workshop on Surface Finish of Silicon Devices (Feb.) 43
World Conference Updates Vocabulary of Measurement Science (Oct.) 225
WWV/WWVH Users Queried (Mar.) 69

X-Y

X-Rays, Beyond (May) 106
Yankee Ingenuity, Energy Needs: Newest Challenge to (Sept.) 202
You, the Computer and Our Society in the Next Two Decades (June) 131

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